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The Reservoir Formation Mode and Mechanism of Longmaxi Formation Shale Gas in the Yuxi area of the Sichuan Basin

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Abstract

The study on the reservoir formation mode and mechanism of Longmaxi Formation shale gas in the Yuxi region of the Sichuan Basin is a fundamental basis for understanding the enrichment law and development potential of shale gas in this area. The shale layers of the Wufeng Formation to Longmaxi Formation in the Yuxi region are buried at depths ranging from 3900 to 4500 meters, with high Total Organic Carbon (TOC) content ranging from 1.96% to 7.88%. The organic matter is of Type I kerogen and is in an overmature stage, exhibiting excellent hydrocarbon generation potential. Research indicates that the gas content in shale increases with burial depth, with the Long11-Long13 layers showing higher gas content, making them the main high-quality gas layers. The ratio of free gas to adsorbed gas is high, indicating significant development potential.The mineral composition of the shale is primarily quartz and clay minerals, with high quartz content facilitating pore development and fracturing, while clay minerals mainly affect adsorbed gas content. Pore types include organic pores, intergranular pores of pyrite, and microfractures, with the Long11 sub-layer exhibiting optimal micro-porosity and superior adsorption and storage performance. Shale gas reservoirs in the Yuxi region have favorable preservation conditions, with few fractures leading to minimal gas loss.Based on regional structural characteristics, a shale gas reservoir formation model of "narrow steep anticlines + fault sealing and covering by wide gentle synclines" is proposed. The study demonstrates that the TOC content, mineral composition, reservoir properties, and preservation conditions collectively influence the enrichment and accumulation of shale gas in the Wufeng Formation to Longmaxi Formation in the Yuxi region, providing important reference for the development of shale gas resources.

Keywords

Shale gas; deep-water shelf shale; gas-bearing properties; Sichuan Basin; Longmaxi Formation; reservoir formation mode and mechanism.

1. INTRODUCTION

The Sichuan Basin is a typical superimposed oil and gas basin and is currently one of the major natural gas producing areas in China. In the process of basin sedimentary evolution, multiple sets of organic-rich mud shale deposits of continental, marine, and transitional facies have developed, leading to abundant shale oil and gas resources [1-3]. The Ordovician Wufeng Formation to Silurian Longmaxi Formation is the main target for shale gas exploration and

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development in the southern Sichuan region. Currently, demonstration areas such as Changning-Zhaotong shale gas demonstration zone, Weirong gas field, and Luzhou shale gas area have been established around this shale formation in the southern Sichuan region. The proven shale gas resources amount to 33.19×1012 m3, with a proven rate of 9.4%, indicating significant exploration potential [4].

Guo Xusheng et al. (2014) proposed the "dual enrichment" law of marine shale gas in complex structural areas, while Zou Caineng et al. (2015) established enrichment models of "structural sweet spots" and "continuous sweet spot zones" for shale gas. These theoretical understandings and methodological advancements have effectively guided and supported the rapid development of China's shale gas industry, facilitating the successful exploitation of shale gas reservoirs in the Wufeng Formation to Longmaxi Formation around the Sichuan Basin and its periphery. Ongoing exploration, evaluation, and development efforts are focused on deep and shallow-pressure shale gas resources [5-6].

Located in the western part of the Sichuan Basin, the Yuxi region experiences frequent geological structural activities, with stable development of the Longmaxi Formation. Clearly defining the accumulation mode and mechanism in the Yuxi region plays an extremely important guiding role in understanding the laws of oil and gas enrichment, determining potential exploration areas for oil and gas, and accurately evaluating oil and gas resources. Currently, there is relatively limited research on the geological conditions and accumulation models of shale gas fields in the Yuxi region. This study focuses on the Yuxi region, leveraging relevant test analysis data and drilling information to analyze the gas-bearing characteristics of the Longmaxi Formation in the Yuxi region and its influencing factors. The study aims to explore the enrichment mechanism and accumulation model of shale gas in the Wufeng Formation to Longmaxi Formation in the Yuxi region, with the goal of providing support for geological research and resource development in this area.

2. REGIONAL GEOLOGICAL BACKGROUND

The Sichuan Basin is situated on the Upper Yangtze Platform, presenting an overall rhombic distribution trending in a northeast direction, surrounded by mountain ranges such as Longmen Mountain, Micang Mountain, and Daba Mountain [7]. Based on the current structural pattern of the Sichuan Basin, it can be divided into six secondary structural units: the western Sichuan low-steep structural zone, the northern Sichuan low-flat structural zone, the central Sichuan low-flat structural zone, the eastern Sichuan high-steep structural zone, the southwestern Sichuan low-gentle structural zone, and the southern Sichuan low-steep structural zone [8].

The study area is located in the southeastern part of the Sichuan Basin, mainly covering the southwestern part of Chongqing Municipality and the southeastern part of Luzhou area (see map). The study area is positioned in the fan-shaped structural development zone to the southeast of the Huaying Mountain fault in the eastern Sichuan Basin of the Upper Yangtze region. On a planar scale, it spans two secondary structural units, namely the southern Sichuan low-steep fold belt and the eastern Sichuan high-steep fold belt. Vertically, it features Jurassic-style interleaved folds, presenting a three-layer geological structure in terms of structural deformation (i.e., Middle-Lower Triassic to Jurassic, Silurian-Permian, and Cambrian and below). The rudimentary structure in the area formed during the Xixi-Yanshan period, with the main body taking shape during the Yanshan period and being finalized during the Himalayan period [9]. The burial depth of the Wufeng Formation to Longmaxi Formation in the study area ranges mostly from 3900 to 4500 meters.

During the Late Ordovician to Early Silurian, the Yuxi region deposited a set of predominantly black shale layers known as the Wufeng Formation to Longmaxi Formation. The Wufeng

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Formation consists of shale rich in graptolites except for the top 1 to 2 meters, which contain fossil-rich calcareous shale or marl (Guanyinqiao layer). The rest of the formation consists of shale rich in graptolites (graptolite shale section), interspersed with thin layers of volcanic ash deposits. The Longmaxi Formation is divided from top to bottom into Long 2 and Long 1: Long 2 primarily consists of gray-green and yellow-green shales and sandy shales, while Long 1 is mainly composed of black and gray-black thinly bedded or blocky shales with well-developed bedding planes and fractures. Based on lithology, electrical properties, and fossil characteristics, Long 1 can be subdivided into Long 1-2 and Long 1-1 sub-segments, with Long 1-1 further subdivided into seven sub-layers from Long 17 to Long 11. The Wufeng Formation to Long 1-1 segment is the shale gas enrichment and development layer in the Yuxi region, also referred to as the gas-bearing shale section.

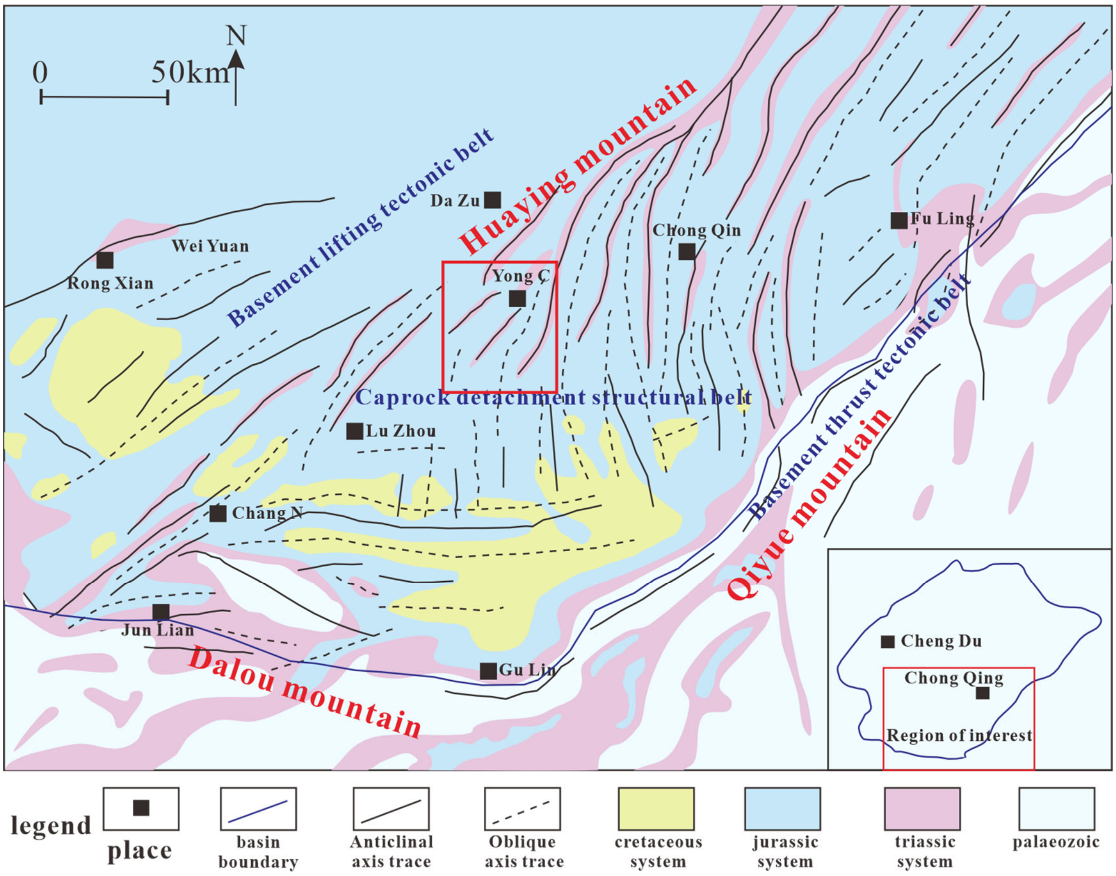

Figure 1. Regional structural map of the research area

3. GAS BEARING CHARACTERISTICS OF SHALE

3.1. Planning

Shale gas content refers to the volume of natural gas contained in one ton of shale at standard conditions (0°C, 101.325 kPa), including free gas, adsorbed gas, and dissolved gas. It is a crucial indicator for the evaluation of shale gas resources and the selection of favorable areas [10-11].

According to gas content test results, the Long 11 sub-layer of the Wufeng Formation to Longmaxi Formation in Well A6 has a gas content ranging from 7.53 to 9.66 m3/t, with an average of 7.07 m3/t. The average gas content is 8.59 m3/t for the Long 12 sub-layer, and 7.12 m3/t for the Long 13 sub-layer. The gas content of the Long 14 sub-layer ranges from 0.73 to 5.339 m3/t, with an average of 2.7 m3/t. The Long 15 sub-layer has a gas content ranging from 0.24 to 4.18 m3/t, averaging 2.19 m3/t. The Long 16 sub-layer shows a gas content ranging from 0.34 to 3.78 m3/t, with an average of 2.28 m3/t. The gas content of the Long 17 sub-layer

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ranges from 0.65 to 3.61 m3/t, averaging 1.18 m3/t. Overall, the gas content of the Wufeng Formation to Longmaxi Formation shale increases with burial depth, with relatively higher gas content in the Long 11 to Long 13 sub-layers.

The development indicators for favorable shale gas layers consider 0.5 m3/t as the lower limit for shale gas content in development layers [12]. In the study area, the gas content of the Wufeng Formation to Longmaxi Formation shale is higher than this development threshold, indicating significant development potential in the shale gas layers of the study area. Specifically, the gas content in the Long 11 to Long 13 sub-layers is notably higher than in other layers, making them primary high-quality gas layers.

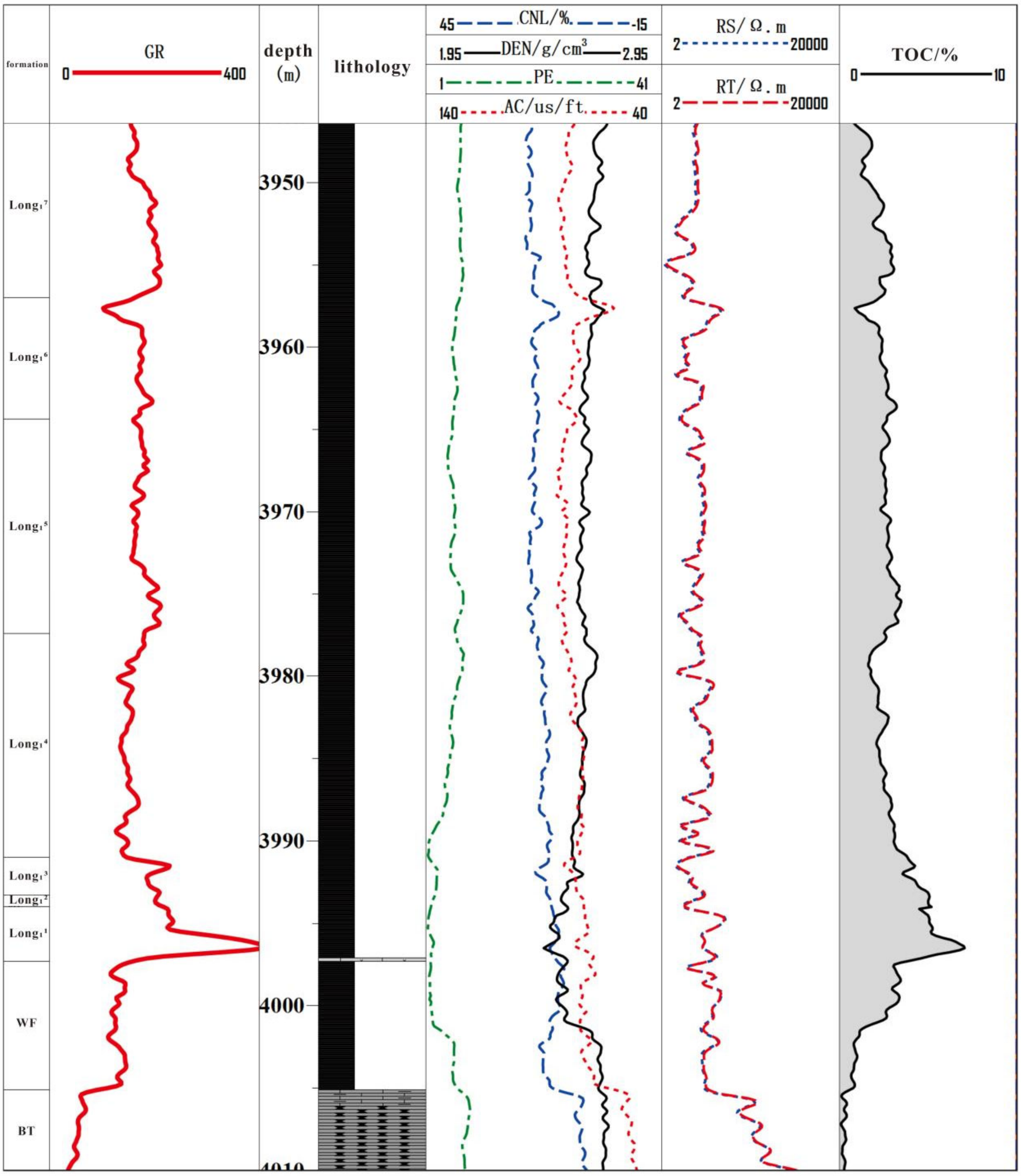

Figure 2. Stratigraphic division column chart of Longmaxi Formation in western Chongqing

In shale gas, free gas exists in the pores and microfractures of the shale in a free state, while adsorbed gas adheres to the surfaces of organic matter and clay minerals, and dissolved gas

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dissolves in oil and water. Due to the limited content of dissolved gas in shale, the gas content in shale primarily refers to adsorbed gas and free gas.

The content of free gas increases continuously with depth, with higher free gas content in the Long 11 to Long 13 sub-layers and lower free gas content in the Long 14 to Long 17 sub-layers. The content of adsorbed gas gradually increases with increasing depth. Overall, in the Wufeng Formation to Longmaxi Formation shale gas, the amount of free gas is greater than that of adsorbed gas, with a relatively higher ratio of free gas to adsorbed gas in the high-quality gas layers (Long 11 to Long 13 sub-layers).

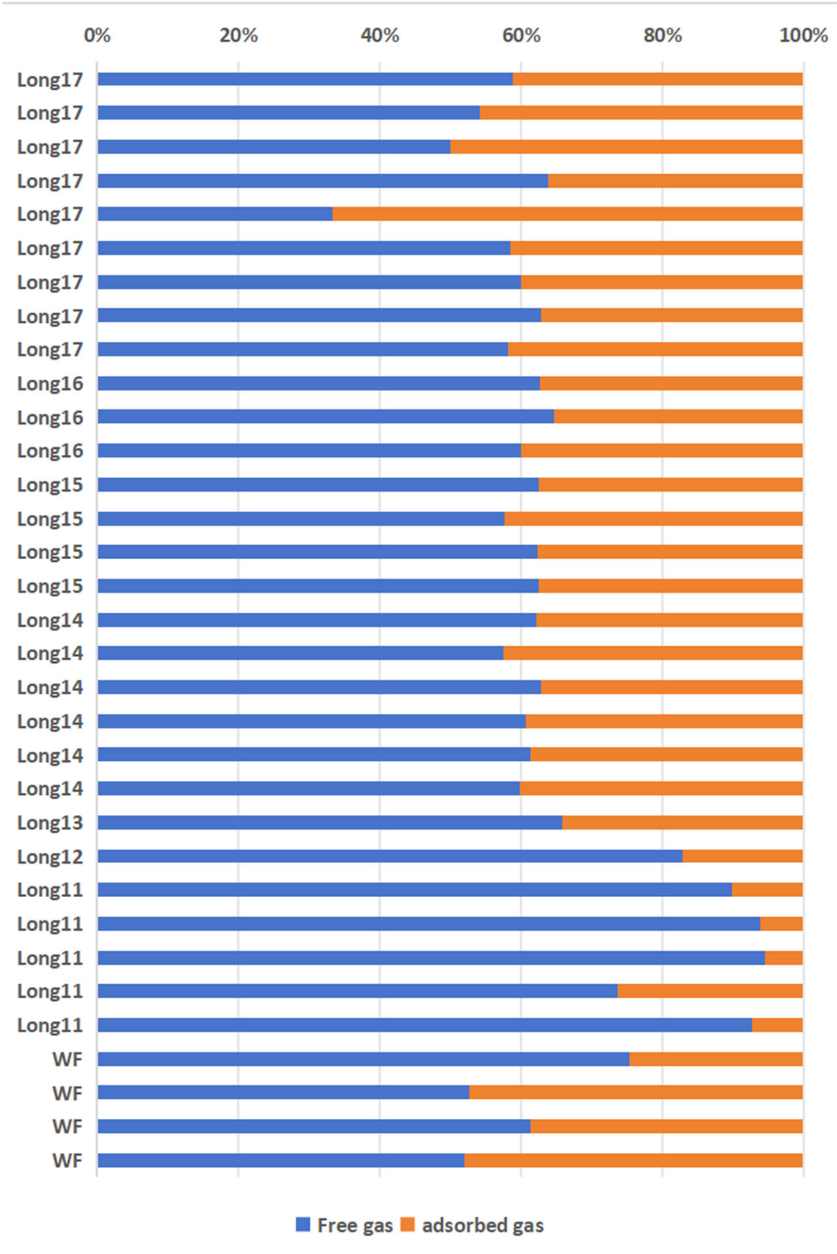

Figure 3. Proportion of free gas and adsorbed gas in shale gas

4. FACTORS AFFECTING GAS CONTENT IN SHALE GAS RESERVOIRS

The content of free gas increases continuously with depth, with higher free gas content in the Long 11 to Long 13 sub-layers and lower free gas content in the Long 14 to Long 17 sub-layers. The content of adsorbed gas gradually increases with increasing depth. Overall, in the Wufeng

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Formation to Longmaxi Formation shale gas, the amount of free gas is greater than that of adsorbed gas, with a relatively higher ratio of free gas to adsorbed gas in the high-quality gas layers (Long 11 to Long 13 sub-layers).

4.1. TOC content and organic matter maturity

Current research indicates that the type of organic matter in shale, total organic carbon (TOC) values, and maturity are important organic geochemical parameters for hydrocarbon source evaluation. Geochemical characteristic analyses were conducted on shale samples from the Long 1-1 sub-segment, the main production layer in the Yuxi region. Examination of the rock core samples from the Wufeng Formation to Longmaxi Formation revealed organic matter vitrinite reflectance results with organic matter vitrinite carbon isotopes (δ13C) ranging from -29.02‰ to -33.94‰.

The maturity of organic matter can be assessed by converting the vitrinite reflectance of samples into equivalent vitrinite reflectance. The formulas are as follows:

Equivalent Ro = 0.618 * Rb + 0.40 (Rb < 3.0%);

Ro = (Rb + 0.2443) / 1.0495 (Rb > 3.0%);

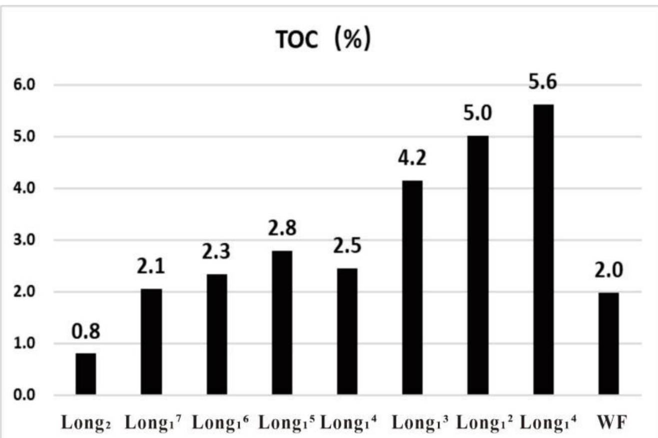
Equivalent Ro = -0.026 * GRo^2 + 0.524 * GRo + 0.5925;

(Rb is the bitumen reflectance and GRo is the graptolite reflectance).

The predominant microcomponents of the organic matter vitrinite are humic, with content ranging from 80% to 95% and averaging 87.86%. The organic matter vitrinite is primarily Type I, exhibiting excellent hydrocarbon generation potential. The calculated equivalent Ro falls within the range of 2.44% to 2.69%. The hydrocarbon source rocks of the Wufeng to Longmaxi Formations are in an over-mature stage, facilitating the generation of gaseous hydrocarbons.

The TOC test results for the Wufeng Formation to Longmaxi Formation in the study area indicate that the main high-quality reservoirs (Long 11 to Long 13 sub-layers) have a TOC distribution ranging from 1.96% to 7.88%, with an average of 4.48%. The TOC content reflects excellent hydrocarbon generation potential in these layers, whereas the average TOC for the Long 14 to Long 17 sub-layers is 2.43, indicating relatively poorer hydrocarbon generation potential. Vertically, the Long 11 to Long 13 sub-layers exhibit the highest TOC content, while TOC variation is minimal in the Long 14 to Long 17 sub-layers. The TOC variation is relatively more pronounced in the Wufeng Formation to Long 13 sub-layers.

Analysis of the relationship between TOC and gas content shows a positive correlation between the two parameters. Overall, the TOC content significantly influences the gas content in the Wufeng Formation to Longmaxi Formation shale.



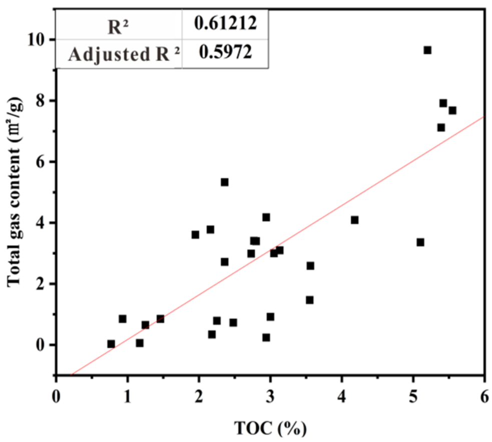


Figure 4. TOC content and its correlation with total gas content

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4.2. Mineral composition and content

Mineral composition is another crucial factor influencing shale gas content. The characteristics of mineral composition not only have a significant impact on reservoir fracturing but also affect shale porosity development and gas content due to the content of clay minerals and quartz. Shale mineral components can be categorized into brittle minerals and clay minerals, each playing a distinct role in shale gas reservoirs. Clay minerals provide numerous gas adsorption sites, enhancing the gas adsorption capacity. On the other hand, changes in the content of brittle minerals like quartz, feldspar, and carbonate minerals mainly affect shale methane adsorption capability. Higher clay mineral content enhances shale gas adsorption properties.

X-ray diffraction whole-rock mineral analysis of multiple shale samples from the Yuxi region indicates that the mineral composition of the Wufeng Formation to Longmaxi Formation shale in the Yuxi region is predominantly composed of quartz and clay minerals. The average quartz content is 43.04%, clay minerals average 32.5%, and carbonate minerals average 14.96%. Generally, the content of brittle minerals such as quartz and feldspar is relatively high, with quartz being dominant and showing an overall increasing trend with depth. Higher silica mineral content facilitates the formation of mineral matrix pores and natural fractures in shale reservoirs, promoting shale gas occurrence and aiding effective hydraulic fracturing in later stages.

The overall clay mineral content decreases with depth, primarily composed of illite with an average content of 56.9%, followed by illite-montmorillonite interstratification with an average content of 25.3%, and chlorite with an average content of 17.8%. No significant presence of montmorillonite or kaolinite was observed.

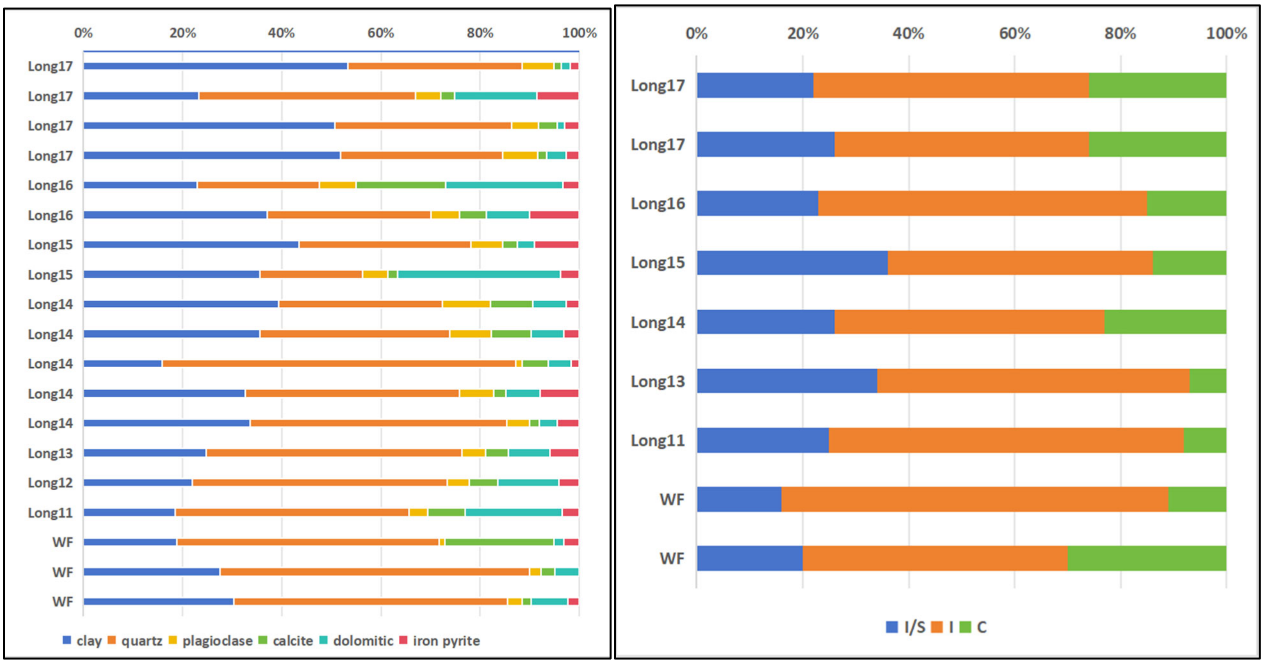

Figure 5. Whole rock mineral composition and clay mineral composition

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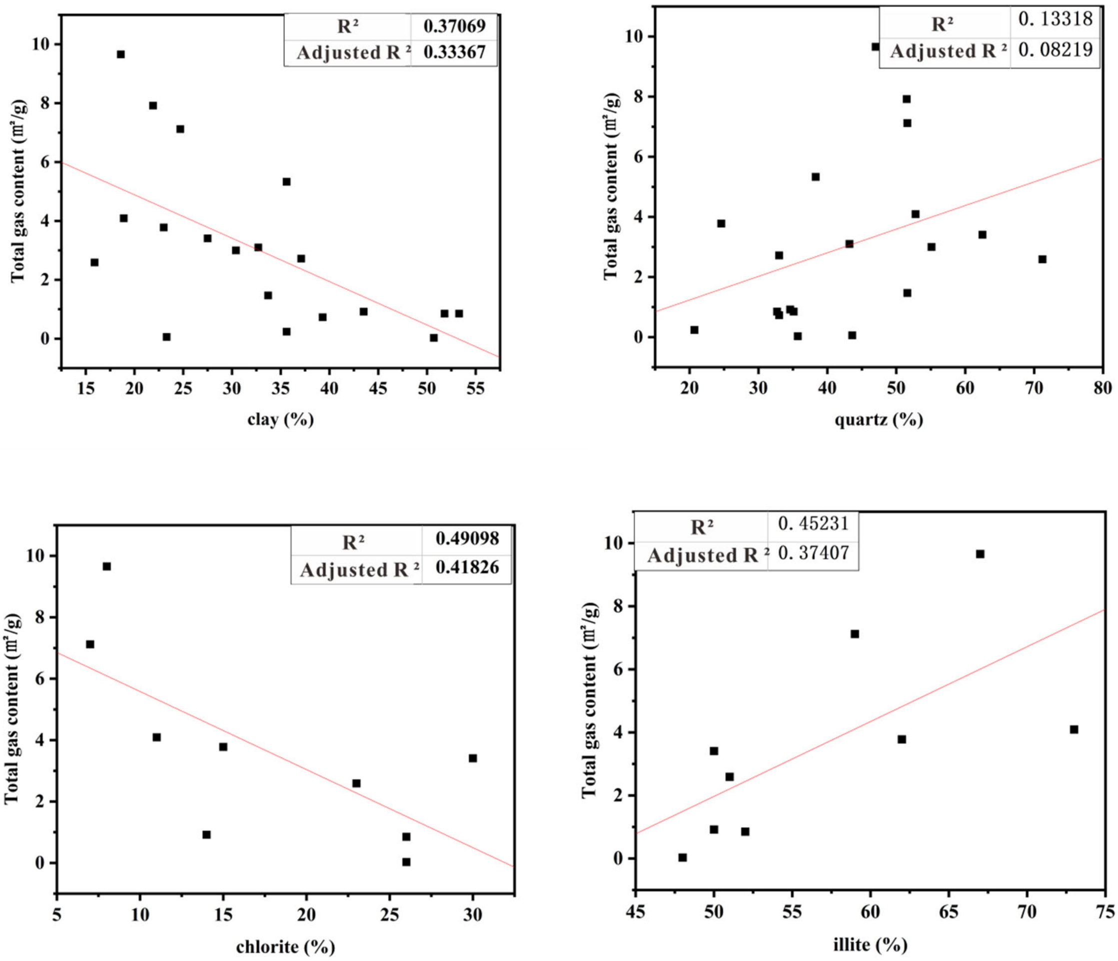

Figure 6. Correlation between clay minerals and total gas content

Correlation analysis between different mineral compositions and gas content reveals a significant negative correlation between total gas content and clay mineral content. The total gas content shows a positive correlation with quartz minerals and illite in clay minerals, and a negative correlation with chlorite content in clay minerals. In general, quartz and clay minerals have a certain degree of influence on shale gas content, with shale exhibiting relatively better gas content when quartz content is higher and clay mineral content is lower.

4.3. Reservoir property characteristics

The types of microscopic pores and porosity in shale play a significant role in the occurrence and enrichment of intra-layer shale gas. Thin section and scanning electron microscopy observations and analyses were conducted on shale samples from the Wufeng Formation to Longmaxi Formation in the Yuxi region, revealing three main types of reservoir spaces: organic pores, inorganic pores, and fractures.

Porosity testing in the Yuxi region for the Wufeng Formation to Long 1-1 sub-segment showed average porosity values ranging from 2.7% to 5.5% across the layers. The porosity values were relatively smaller in the Wufeng Formation (3.15%) and Long 17 sub-layer (3.8%), while there was minimal variation among the Long 11 to Long 16 sub-layers (ranging from 4.13% to 4.88%).

Overburden depth experiments demonstrated that the matrix permeability of the Wufeng Formation to Longmaxi Formation shale in the Yuxi region ranged from 0.526×10^-3 to 16.8×10^-3 mD, with an average of 5.505×10^-3 mD. Overall, the shale exhibited characteristics

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of low porosity and low permeability. The porosity decreased with increasing depth in the Longmaxi Formation, correlating with higher calcium content in the shale.

Under FE-SEM observation, the Longmaxi Formation shale in the Yuxi region commonly exhibits abundant organic pores, interstitial pores of pyrite, intergranular pores, intragranular pores, dissolution pores, and microcracks. The presence of biogenic silica in deepwater shelf environments facilitates the formation of organic pores, while deep-seated overpressure conditions contribute to the preservation of these organic pores. Overall, organic pores are more developed than inorganic mineral pores, with organic pores in the Long 11-Long 13 sub-layers being more developed compared to upper sub-layers.

Based on combined analysis of nitrogen adsorption and low-pressure carbon dioxide adsorption experiments on micropores, mesopores, and macropores regarding their contributions to specific surface area and pore volume, the Long 1-1 sub-segment of the Long 1-1 sub-segment showed that micropores, mesopores, and macropores contributed 32.85%, 65.56%, and 1.59% to the specific surface area of pores, respectively. For pore volume, the contributions were 6.15%, 72.01%, and 21.83% for micropores, mesopores, and macropores, respectively. In the microscopic pores of the Wufeng Formation to Longmaxi Formation shale in the Yuxi region, micropores make a significant contribution to specific surface area but a smaller contribution to pore volume. The development of micropores greatly enhances the adsorption capacity of materials, particularly in gas adsorption and storage applications. The Long 11 sub-layer has the highest contribution rate of micropores, indicating stronger adsorption and storage performance in this layer. Mesopores dominate the pore structure of these samples, offering a large surface area and volume suitable for gas or liquid storage and transport. The Wufeng Formation has the highest contribution rate of mesopores, indicating well-developed pores with better storage capacity. Macropores make a substantial contribution to pore volume, especially in the Long 12 sub-layer where the macropore volume contribution rate reaches 24.31%. The well-developed macropores in this layer facilitate rapid fluid flow and expulsion.

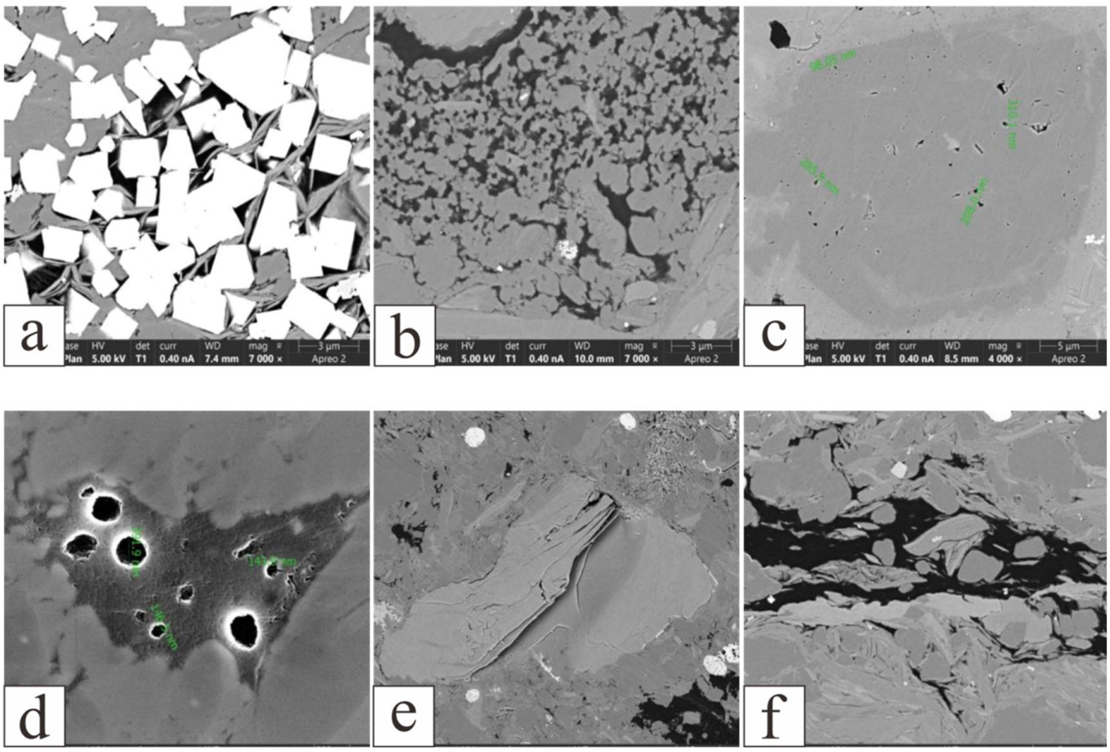

Figure 7. Typical pore types of shale in western Chongqing region

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Table 1. Longmaxi Formation shale micropores, mesopores, and macropores' contributions to specific surface area and pore volume.

formation	Contribution rate of pore specific surface area			Contribution rate of pore volume		
	micropore	mesopore	macropore	micropore	mesopore	macropore
Long14	30.48%	66.73%	2.79%	3.81%	67.33%	28.86%
Long13	35.12%	63.87%	1.01%	7.86%	74.01%	18.13%
Long11	32.65%	66.14%	1.21%	6.72%	74.62%	18.66%
WF	33.15%	65.51%	1.35%	6.22%	72.09%	21.69%
Average contribution rate(%)	32.85%	65.56%	1.59%	6.15%	72.01%	21.83%

4.4. Storage conditions for shale gas

The preservation and structural conditions play a crucial role in the exploration and development of marine shale gas in complex structural areas. Good preservation conditions are key factors for the enrichment and high productivity of shale gas. The intensity of structural modification controls the preservation conditions of shale gas reservoirs, and shale formations with high gas content often have favorable regional cap and basement conditions.

Structural factors such as faults have a significant impact on the preservation and enrichment conditions of shale gas. On one hand, faults can disrupt the sealing of shale gas reservoirs, serving as pathways for vertical migration of shale gas. When faults penetrate the cap and basement, their connectivity and scale directly influence the extent of shale gas migration. The more disconnected layers and the larger the fault spacing in the Longmaxi Formation, the poorer the reservoir's seal, leading to less favorable conditions for shale gas accumulation. On the other hand, not all faults have adverse effects on shale gas enrichment. Appropriately sized faults, along with their associated natural fractures, may provide additional storage space for shale gas and facilitate desorption and intra-layer accumulation. Such faults may have a minor destructive impact on shale gas reservoirs and could instead serve as favorable factors for shale gas enrichment.

Furthermore, geological structures influence the preservation and enrichment of shale gas by controlling fold systems, fracture distribution, and composite patterns. The degree of fold deformation determines the distribution of fractures, while the form of fractures dictates stratal deformation and fracture development, thus governing the preservation and enrichment of shale gas.

The nature and development scale of faults are related to the intensity of structural modification. Three structural deformation stages, namely the late Yanshan Movement in the Late Cretaceous to Cenozoic, the early Himalayan Movement, and the late Himalayan Movement, have led to large-scale folding and thrusting in the eastern Sichuan Basin. Controlled by differential compression, significant differences in deformation characteristics and fault systems exist between different structural belts and within different parts of the same structural belt, forming the basic structural framework in the study area.

The Yuxi region exhibits complex geological structures with well-developed faults. The formation pressure coefficient of the reservoir interval ranges from 1.86 to 1.98, indicating a normal pressure gas reservoir. It is generally believed that areas near large faults or with well-developed microcracks have poorer preservation conditions for shale gas reservoirs. In regions where large faults are underdeveloped or absent, the expulsion of hydrocarbons from shale is hindered, resulting in less hydrocarbon expulsion and more residual hydrocarbons in shale,

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overall favoring the preservation conditions for shale gas and facilitating shale gas accumulation. However, extensive development of microcracks can damage shale gas reservoirs, leading to varying degrees of reduction in shale gas content and impacting the economic viability of shale gas reservoirs.

Table 2. Fracture classification standard

Fracture classification	Fracture classification method	The impact on storage conditions
First-order fracture	Breaking through the cover layer of the area upwards and breaking downwards to below the Wufeng Formation, the fault distance is usually greater than 300 meters	destruction
Second-order fracture	Cut through the top and bottom of the reservoir, but not through the regional cap layer, with a fault distance of 100-300m	Has a certain impact
Third-order fracture	Completely disconnect the shale gas reservoir, without cutting through the top and bottom plates, with a fault distance of less than 100m	Basically no impact
Fourth-order fracture	Incomplete disconnection of shale gas reservoir	no effect

In summary, in the Yuxi region, the Wufeng Formation to Longmaxi Formation has not been eroded and exposed, leading to favorable preservation conditions for shale reservoirs. Shale gas is less prone to lateral or vertical migration and dispersal, thereby increasing the gas content within the shale formations.

5. SHALE GAS RESERVOIR FORMATION MODEL

The formation and accumulation patterns of shale gas vary across different regions and types. Various factors such as sedimentary environments, thermal evolution levels, cap rock properties, and structural preservation conditions play diverse roles in the enrichment and accumulation of shale gas. In the Yuxi region, the Wufeng-Longmaxi formations are influenced by compressional tectonic stress, resulting in the formation of faults within the strata. On one side of the fault, shale gas is affected by buoyancy and diffusion, migrating towards structurally higher positions and getting trapped laterally by reverse faults, leading to gas accumulation below the fault plane. On the other side, shale gas disperses laterally along the dip.

Narrow steep anticline faults exhibit closure characteristics due to thrusting, providing effective sealing for the widespread shale gas within broad gentle anticlines. In the overlying and underlying layers of high-quality shale gas reservoirs, the top and bottom rock layers of continuous sedimentary strata are thick and densely compacted. Additionally, the sealing effectiveness of pressure-twisted reverse faults is strong, the degree of structural deformation is low, and the anticline structures are intact. Moreover, the shale gas layers contain numerous rounded organic pores and open microfractures, establishing a well-preserved pore network system that facilitates gas storage and migration. These consistently favorable preservation conditions enable the extensive gentle anticline Wufeng-Longmaxi shale gas formations to establish a self-contained system.

Based on the characteristics of gas accumulation in the Yuxi region, the shale gas accumulation model of the Wufeng-Longmaxi formations can be categorized as the "narrow

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steep anticline + fault sealing and blocking - broad gentle anticline continuous distribution" shale gas accumulation model.

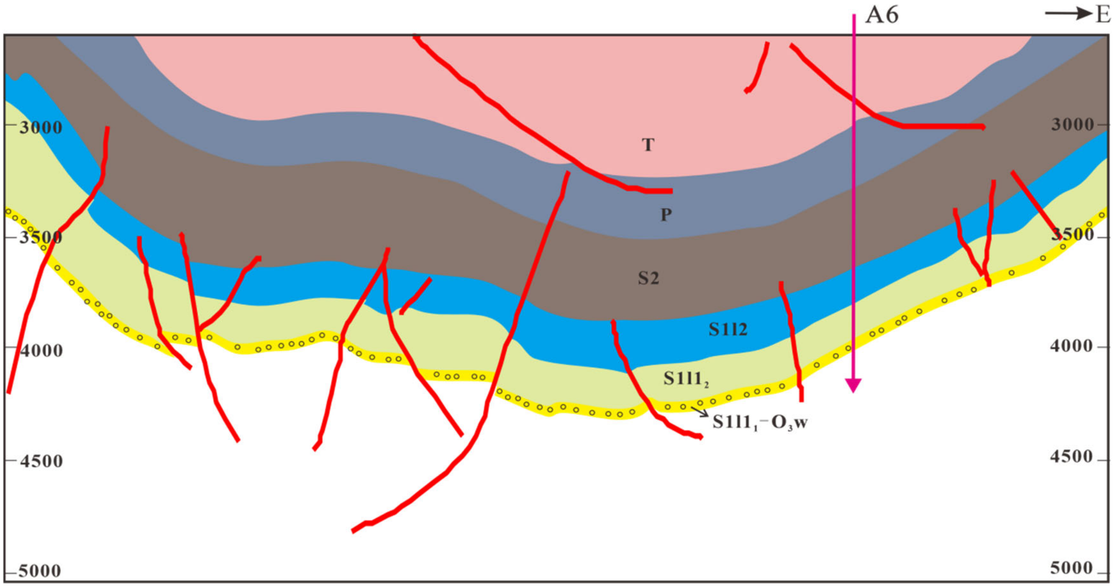

Figure 8. Reservoir formation model of Longmaxi Formation shale gas in Yuxi area

6. CONCLUSION

(1) In the Yuxi region, the overall gas content of the Wufeng-Longmaxi shale increases continuously with increasing burial depth. The Long11-Long13 layers exhibit relatively high gas content, indicating significant development potential for shale gas reservoirs in the study area, making them prime targets for high-quality gas reservoirs. Additionally, the high-quality gas layers (Long11-Long13 layers) exhibit a high ratio of free gas to adsorbed gas.

(2) In the Yuxi region, the maceral composition of kerogen is dominated by sapropelic components, with Type I kerogen being prevalent. These kerogens possess excellent hydrocarbon generation potential, and the Wufeng-Longmaxi source rocks are in an overmature stage, favoring the generation of gaseous hydrocarbons. Total Organic Carbon (TOC) tests on the Wufeng-Longmaxi formations indicate excellent hydrocarbon generation potential, with TOC showing a positive correlation with gas content. The TOC content, mineral composition, reservoir properties, and preservation conditions of the Wufeng-Longmaxi shale in the study area play a significant role in controlling gas content. The Longmaxi shale in the Yuxi region commonly exhibits abundant organic matter pores, intergranular pores of pyrite, interparticle pores, intraparticle pores, dissolution pores, and microfractures. The regional cap rock development, organic-rich shale top and bottom lithology, poor fault development, and favorable preservation conditions contribute to the retention of shale gas.

(3) In the Yuxi region, the Wufeng-Longmaxi formations are influenced by compressional tectonic stress, resulting in the formation of faults within the strata. On one side of the fault, shale gas is affected by buoyancy and diffusion, migrating towards structurally higher positions and getting trapped laterally by reverse faults, leading to gas accumulation below the fault plane. On the other side, shale gas disperses laterally along the dip. Based on the characteristics of gas accumulation in the Yuxi region, the Wufeng-Longmaxi formations can be classified as the "narrow steep anticline + fault sealing and blocking - broad gentle anticline continuous distribution" shale gas accumulation model.

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